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An analytical literature review of stand-alone wind energy conversion systems from generator viewpoint

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ABSTRACT

The purpose of this paper is to provide an analytical review of wind turbine-generator systems for stand-alone applications. The review focuses on variable-speed wind turbines, as the future trend in wind energy conversion, in contrast with the traditional fixed-speed wind turbines. Indirect-drive and direct-drive turbines are comparatively evaluated. The concerns about long-term availability of permanent magnet materials and its impact on the future of permanent magnet synchronous generator are addressed. Having cost and efficiency in mind, viability of indirect-drive squirrel cage induction generator for stand-alone wind energy conversion systems is discussed. As an efficient induction machine design, permanent magnet induction generator is also examined. Finally, the potential of using switched reluctance machine, as a generator, in a direct-drive wind turbine system is investigated.

Contents

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1. Introduction

Recently, utilization of wind energy has achieved a rapid growth in Europe, North America and Asia. Global Wind Energy Council (GWEC) reported that the total capacity of wind energy, installed in 2012 alone, exceeded 44 GW worldwide [1]. By 2020, European Union aims to have 20% of its electricity demand supplied by wind energy [2]. The US Department of Energy reports that wind energy can supply 20% of the country′s total demand by 2030 [3]. Although still lagging behind many other countries in support for wind energy, Canada plans to stay on track by having 20% of its demand supplied by wind energy by the end of 2025 [4]. Asia is still the largest regional market for wind energy. In China alone, the target is to install 150 GW of wind power capacity by 2020 [5].

Along with such a rapid growth, an enormous volume of research and development is being undertaken in the academia and industry on wind energy conversion systems (WECS). Different configurations of grid-connected WECS have been reviewed in a number of papers and books based on the types of generator and power electronic converter employed [6–15]. However, there is, to the best of the knowledge of the authors, insufficient review and comparative study on off-grid WECS.

Off-grid or stand-alone small wind turbines provide a very attractive renewable energy source for remote communities and small business. These wind turbines help in reducing the stress on the grid, diminish the pollution [16] and save on fuel cost by reducing or even eliminating the need for diesel generators, which consume a lot of polluting fuel, have high operating and maintenance costs, and may require additional significant costs if installed in a remote area where fuel transportation and refueling is a complicated mission [17]. Moreover, stand-alone wind turbines can be installed wherever wind resource is adequate and there is no access to the grid, or connection to the grid is very costly [18], or is not permitted or is difficult due to the required official approvals. Although the concept of operation is the same in both on-grid and off-grid WECS, the absence of grid in the off-grid case adds to the hardware and control requirements. In spite of the fact that wind energy is intermittent and cannot be dispatched to meet the assigned commitment, connection to the grid allows for extracting maximum power available from wind resources at any moment of time. In contrast, for an off-grid WECS to satisfy time-varying power demand and maintain balance of power, at least an energy storage unit is required to compensate for the power deficit and absorb the excess power. In some remote areas, a hybrid system might be required to complement wind power with other sources such as photovoltaic, small hydro and diesel generator. A combination of wind and solar energy is the most common complementary system [16]. This combination is frequently integrated with diesel generators to form a micro-grid, supplying off-grid communities. [19]. In such cases, a more complicated control is required in order to achieve an efficient power management [20]. Another issue with off-grid WECS is the reactive power required by some generator types that has to be supplied by a VAR source such as a capacitor bank, synchronous condenser, SVC or STATCOM [21].

Unlike fixed-speed wind turbines, variable-speed wind turbines require a partial- or full-scale power converter for power flow control, maximum power point tracking and ensuring a high quality for the power delivered. Fixed-speed wind turbines, in general, use squirrel-cage induction generator, with no power electronic interface [8–10]. On the contrary, variable-speed wind turbines enjoy a rather wide range of options for appropriate generator and power converter types. Asynchronous and synchronous machines are the most common generators employed in variable speed wind turbines. If the generator is coupled to the turbine′s shaft through a gearbox, the wind turbine is called indirect-drive or geared-drive wind turbine. If no gearbox exists, the wind turbine is called direct-drive or gearless-drive wind turbine. Selection of the right generator is of key importance to successful capturing of wind energy under different wind speed conditions, especially at low wind speeds, where the low power available has to be processed by a high-efficiency conversion system. Selection of electrical generator for stand-alone turbine has been briefly discussed in reference [22]. Induction and synchronous generators are compared and it has been concluded that the generator for stand-alone turbine must be a permanent magnet (PM) machine in order to avoid excitation requirement. Nevertheless, there are other issues that have to be addressed in addition to excitation requirements. Reference [23] has reviewed the key technologies of small-scale off-grid wind turbines. However, among all possible machines, the review has focused on PM generators only. PM generators, especially direct-drive PM synchronous generators, are the most commonly used electric machine for small-scale wind turbines [23] and have been of interest to many researchers as a typical solution for stand-alone WECS [24–28]. However, the attraction to direct-drive PMSG has been based on the criteria of high power density and reliability only. Other factors such as cost, and maintenance and control requirements should also be considered for a more thorough evaluation. Moreover, there is no definite proof that a direct-drive wind turbine is more reliable than an indirect-drive wind turbine [29]. A good number of published papers, listed in [30], have focused on induction generators as mature machines for stand-alone wind energy applications. Squirrel-cage induction generator, in particular, has been recommended by [31–34] as a simple, robust, brushless and cost-effective generator for stand-alone WECS. However, the attractiveness of such a generator may diminish if its efficiency is considered.

The above discussion points to the fact that a more comprehensive list of factors should be considered in the study leading to selection of the most appropriate generator for a stand-alone WECS under specific conditions. Some principles for generator selection in small off-grid wind turbines were listed in [23]. However, some important factors such as control requirements and construction complexity were not considered. Furthermore, excitation requirement was not an issue in [23], since the paper has focused on PM generators only. Therefore, in order to select the right generator for a stand-alone wind turbine, there is a need for a thorough study, considering all possible options, to be conducted on the basis of efficiency, reliability, cost, operation and maintenance requirements, construction complexity, control complexity, excitation requirements and noise level associated with each generator type.

This paper makes an analytical review and a comparative evaluation of the main configurations for variable-speed off-grid WECS from the generator type viewpoint to enable selection of the most appropriate solution subject to the given conditions. Besides covering conventional generator types, the potential of permanent magnet induction generator and switched reluctance generator for WECS application will also be investigated. To the best of the authors′ knowledge, such a thorough critical review, considering all possible generators and all factors stated, has not been conducted before. In addition to the outcomes of the evaluation process, the paper can serve as a source of information and relevant references for researchers interested in stand-alone wind turbine systems.

The paper starts with describing main components of variable-speed stand-alone WECS. Then, an overview of different wind generator systems, available in the market and reported in the literatures, is given. The appropriateness of each generator for small-scale off-grid WECS is examined based on the criteria stated

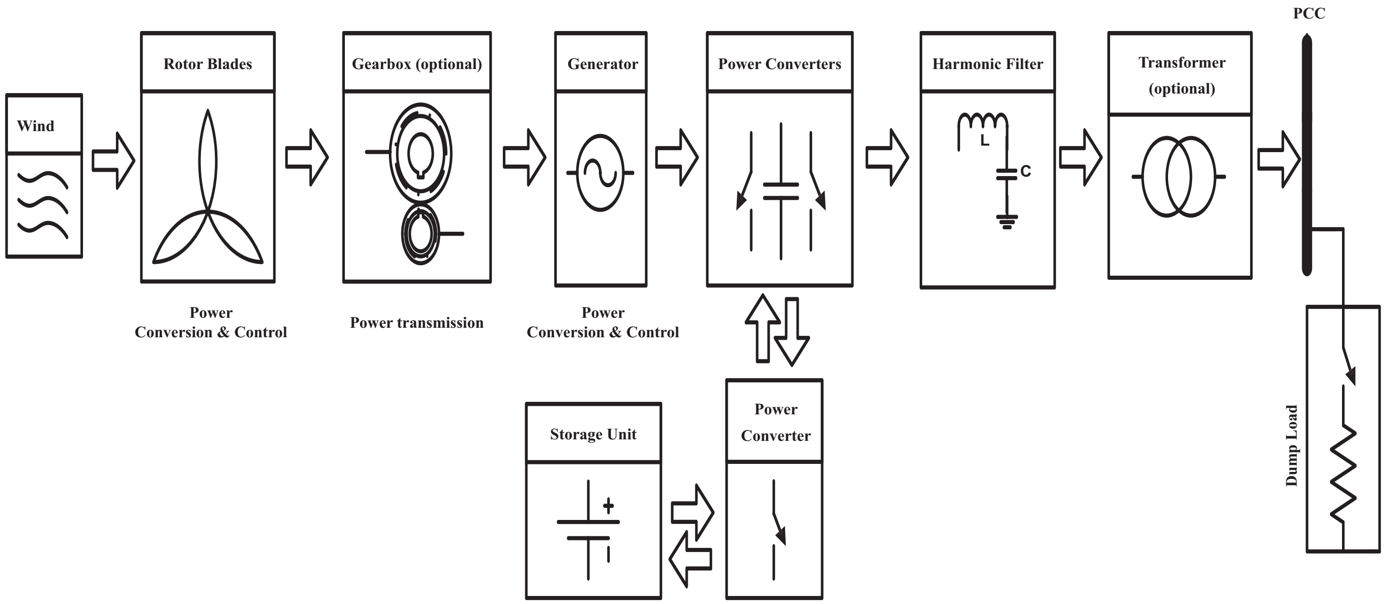

Fig. 1. The components of a variable-speed, stand-alone wind energy conversion system.

earlier. Generators which meet most of the requirements are compared with one another. Some real data from the wind energy market is utilized to help in the evaluation process. Finally, some conclusions are drawn based on the analysis performed.

2. Components of variable-speed stand-alone WECS

As shown in Fig. 1, a typical variable-speed, stand-alone WECS, with full-scale power converters, consists of

1. wind turbine blades and rotor,
2. gearbox (in geared-drive systems),
3. generator,
4. power electronic converter (generator-side),
5. DC link (energy storage device),
6. power electronic converter (load-side),
7. low-pass harmonic filter,
8. transformer,
9. storage unit such as (battery and/or ultracapacitor),
10. power electronic converter (storage-side),
11. dump load (to absorb excess power when the storage unit is fully charged),
12. control circuits including maximum power point tracking (MPPT) control on generator-side converter, voltage/frequency/power factor control on load-side converter, and power/energy management control on storage and dump load-side converters.

3. Generators used in stand-alone WECS

In this section, a comparative evaluation of the generators commonly-used in stand-alone WECS is presented.

3.1. Asynchronous generators

Asynchronous or induction generators feature very mature technology, low maintenance, low cost, good dynamic response and simple operation and control. They are very robust in construction and provide natural protection against short circuit. However, an induction generator (IG) needs to be continuously excited by a source of reactive power in order to generate voltage and supply active power. In stand-alone wind turbines, this reactive power can be supplied by either an external VAR source, such as switched capacitors, or a power electronic converter [35]. In this case, they are called self-excited induction generators (SEIG). A gearbox is required to match the low turbine speed to the high speed required by the generator. Based on the rotor type, IGs are classified into wound-rotor induction generator (WRIG) and squirrel-cage induction generator (SCIG). In WRIG, the rotor contains a three-phase winding similar to that of the stator, whereas the rotor of SCIG consists of short-circuited conducting bars, shaped like a squirrel cage. The WRIG can be reconfigured as doubly-fed induction generator (DFIG) or brushless doubly-fed induction generator (BDFIG). In the following, the applications of WRIG, DFIG, BDFIG and SCIG in WECS will be described. Permanent magnet induction generator (PMIG), a relatively new IG-based machine, will also be examined in Section 5.

3.1.1. WRIG

Fig. 2 shows a simplified configuration for a stand-alone, variable-speed WRIG-based WECS. The stator is connected to the PCC (point of common coupling), while the rotor is connected to an external variable resistance (R_{ext}) that is controlled by a power electronic converter. By varying the value of *Rext*, the generator can run at different operating points. A soft starter is needed in this configuration to reduce the inrush current at start-up, if the transformer and VAR compensator are not sized properly to cope with the starting requirements. Stand-alone WRIG is simply controlled to produce stable voltages with constant amplitude and frequency even though rotor speed is varied by several percent [36,37]. Soft starter requirement, limited speed range and reduced efficiency due to the power loss in the external resistance are the major drawbacks of this configuration. Moreover, the presence of slip ring and brushes, requiring regular maintenance and replacement, makes WRIG not an attractive option for remote area applications, where maintenance is difficult and costly. This problem can be overcome by realizing a variable resistor in series with the rotor winding on the generator shaft using a fixed resistor and a converter that receives control signals optically; however, this increases heat dissipation inside the

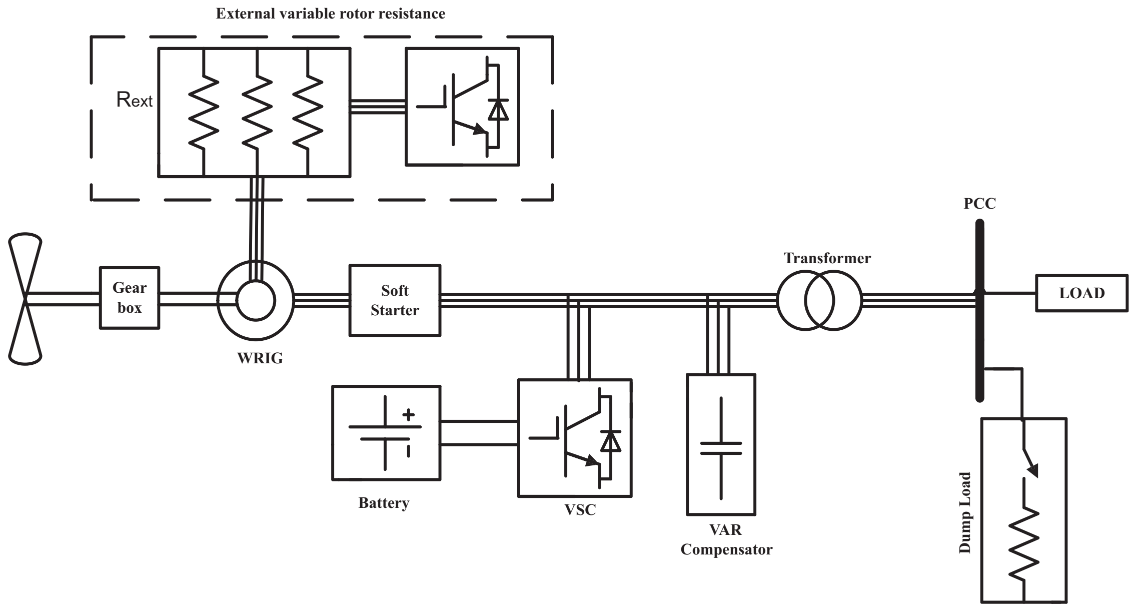

Fig. 2. WRIG-based stand-alone WECS.

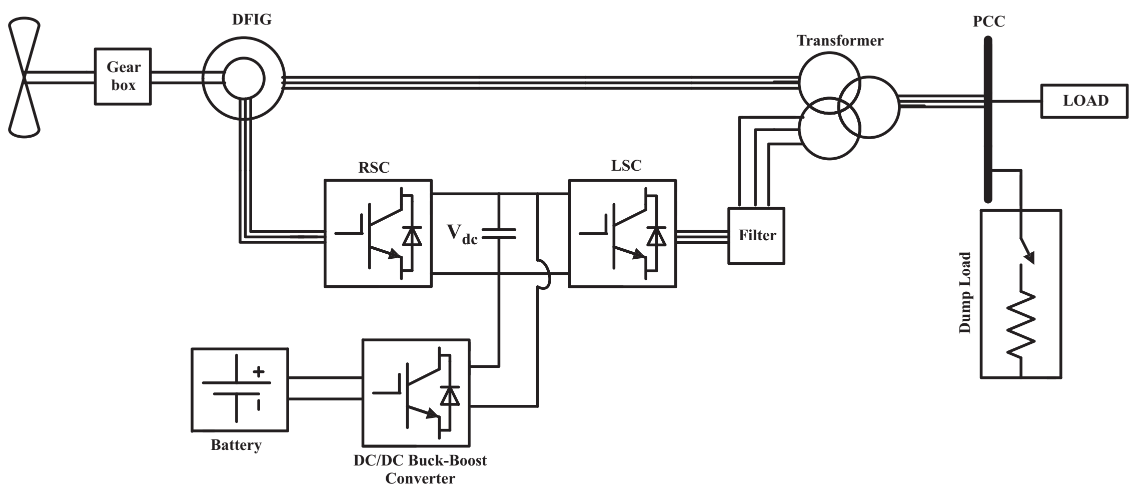

Fig. 3. DFIG-based stand-alone WECS.

generator and limits the speed variation range to approximately 10% of rated speed [38].

3.1.2. DFIG

A DFIG-based stand-alone WECS is constructed by connecting the stator directly, and the rotor via a power electronic converter, to the PCC or the load bus, as shown in Fig. 3. The flow of power through the stator is unidirectional, while the direction of power flow through rotor depends on the operational mode of generator. If the generator is operating below synchronous speed or sub-synchronously, the power is received by the rotor. If the generator is operating above synchronous speed or super-synchronously, the rotor delivers power. Dynamically, DFIG may operate at up to 30% above the synchronous speed or at up to -0.3 pu slip; hence the rotor power converters should be rated at 30% of the stator power [12]. This significantly reduces the rating and cost of power converters and harmonic filters compared to those of WECS with full-scale power electronic converter. This feature makes DFIG a preferred choice in high-power grid-connected wind energy conversion systems, due to the huge economic gains resulting from reduced sizes of power converters and filters. However, the economic gain may not be considerable in the case of stand-alone wind turbine systems, where level of power is relatively low (ranging from a few kilowatts to a few hundred kilowatts). Another advantage of DFIG is that its stator can be excited from the rotor circuit via the power converters, and hence the need for an external VAR compensator can be eliminated.

In the typical arrangement shown in Fig. 3, the required reactive power is generated by the load-side converter (LSC), supported by an energy storage system. The speed of the generator, and hence the direction of the reactive power, is controlled by the rotor-side converter (RSC) [39], while the load-side converter is responsible for regulating the DC link voltage [40]. Different control strategies that have been developed and investigated by [41–43], have demonstrated the ease of controlling the DFIG in stand-alone wind energy applications, especially from the voltage regulation point of view. However, the rotor voltage and current need to be carefully controlled during the initial transients, as they can be too high to be handled by the reduced-size converters [44]. Like WRIG, DFIG has the drawback of unavoidable use of brushes and slip rings, reducing its reliability and increasing

its maintenance requirements. To overcome this problem, a new configuration called brushless DFIG (BDFIG) has been developed and adopted in wind energy conversion systems.

3.1.3. BDFIG

BDFIG consists of two cascaded wound-rotor induction machines, one for generation and the other one for control [11]. Alternatively, BDFIG can be constructed by a single stator, with two 3-phase windings, and a special cage rotor [45]. In both cases, BDFIG has two groups of stator windings. The two groups are referred to as power winding (PW) and control winding (CW). As shown in Fig. 4, the PW is directly connected to the PCC, while the CW is connected to the PCC through two back-to-back reduced-size power converters, i.e., machine-side converter (MSC) and load-side converter (LSC). In order to avoid direct coupling between PW and CW, their pole numbers should not be the same [46]. Instead, cross-coupling between PW and CW should be established via the rotor by selecting the rotor circuit pole number to be equal to the sum of PW and CW pole-pair numbers [45].

BDFIG's benefits are similar to those of DFIG [47]. Nevertheless, its size is larger, and the complexity of its assembly and control is higher [48]. This is due to the cascaded- machine or double-stator design. Despite these disadvantages, BDFIG is still attractive for large grid-connected wind turbines, especially for off-shore applications where wind turbines have to be very reliable and nearly maintenance free. Indeed, many papers and projects have demonstrated the efficient performance of BDFIG for the large off-shore grid-connected wind turbines, even during unbalanced grid conditions [46,49–51]. In stand-alone wind energy conversion system applications, the large size and complexity of BDFIG is an issue which may defeat the advantage of reduced power converter, especially for small wind turbines.

Brushless doubly-fed reluctance generator (BDFRG) is another design with reluctance rotor instead of wound rotor in BDFIG. Although BDFRG is more efficient and reliable than BDFIG, it still has a complex rotor design and a large size due to a lower torque–volume ratio [11].

3.1.4. SCIG

Unlike WRIG, with insulated rotor windings accessible via slip rings and brushes, SCIG has a rotor composed of longitudinal conductive bars set into grooves and short circuited by shorting rings. The problems of brushes and slip rings in WRIG and DFIG, and the complexity of BDFIG, have been overcome in SCIG. Thus, SCIG is the smallest in size, lowest in cost and most robust in structure among the four configurations of IGs [52,53]. However, a SCIG-based WECS requires full-capacity power converters to harvest the maximum power available from wind and achieve full control of both active and reactive power. As a mature machine in wind energy applications, SCIG-based wind turbine systems have been of interest in many research projects including simulator design, emulator set-up, novel power converters and control schemes [54–60], and self-excitation and voltage build up techniques in stand-alone and hybrid micro-grids [21,61,62]. Since SCIG is one of the highly recommended generators for off-grid applications [31,32], its possible configurations will be discussed in detail in Section 4.

3.2. Synchronous generators

Stator of a synchronous generator (SG) has essentially the same design as that of an induction generator. Rotor of SG can be either cylindrical (i.e., distributed winding with a uniform air gap) or salient (i.e., concentrated windings on the poles and non-uniform air gap). With short axial length, large diameter and a relatively high number of poles, the salient-pole rotor SGs are usually used for low-speed applications [48,63]. The main advantage of synchronous generator-based WECS over induction generator-based WECS is the possibility of eliminating the need for gearbox, and hence reducing maintenance requirements and increasing the system reliability and efficiency. Therefore, wind turbine systems using SGs are often referred to as direct-drive or gearless wind turbines [7]. Although elimination of gearbox can save money, direct-drive generators are larger, heavier and more costly due to the need for higher number of rotor poles in order to lower the generator speed requirement and match the turbine speed with no gearbox. Thus, indirect-drive SG with small number of poles is still an acceptable solution in the wind energy market [7,8,64]. In the following, the application of the two types of SG, i.e., wound-rotor synchronous generator (WRSG) and permanent-magnet synchronous generator (PMSG), in wind energy conversion systems, are described.

3.2.1. WRSG

The rotor field winding of the WRSG requires DC excitation, which can be provided by either an external DC source through

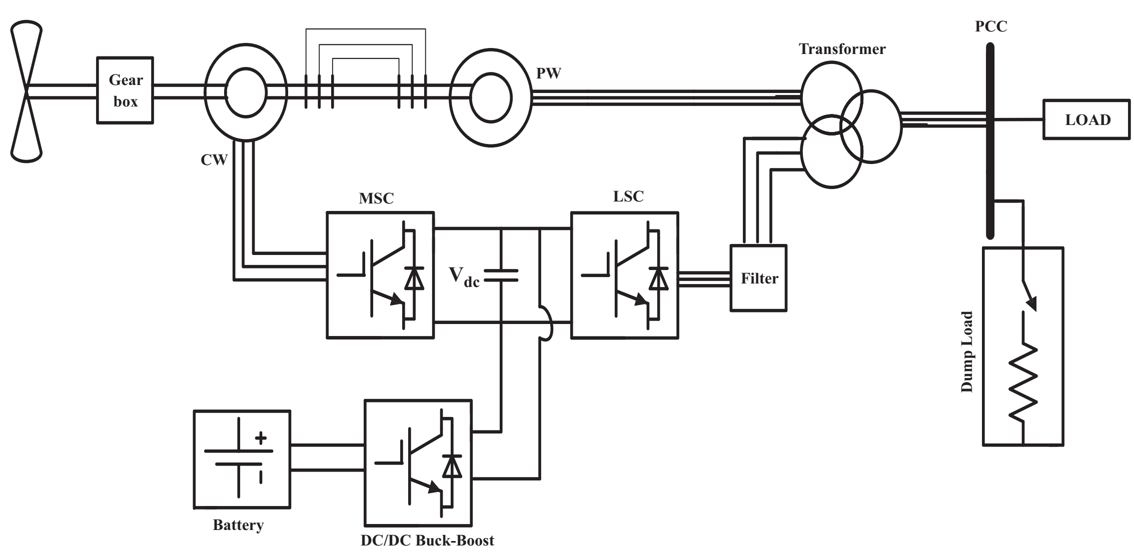

Fig. 4. BDFIG-based stand-alone WECS.

slip rings and brushes or a brushless exciter. The former method is simple, but requires regular maintenance for brushes and slip rings, whereas the latter option needs much less maintenance, but is more complex and expensive due to power electronics involvement and the need for an auxiliary AC generator. As WRSG is excited by DC current, it is also known as electrically excited synchronous generator (EESG). Fig. 5 presents a typical stand-alone WECS based on EESG. The generator-side converter (GSC) is responsible for MPPT, while the load-side converter (LSC) controls the voltage and frequency at PCC under unbalanced loads, provided that the DC link voltage is regulated by implementing a power management strategy that controls the power transactions of battery and dump load under different load and wind speed conditions. The rotor field winding is usually excited by an auxiliary DC source via a DC/DC converter controlled in order to maintain a constant voltage at the stator terminals. An automatic voltage regulator (AVR) can also be used for such purpose [65]. Different control schemes for stator voltage regulation in stand-alone WRSG are described in [66].

WRSG-based stand-alone WECS has been mentioned by [67] as a promising alternative for serving remote load demands. However, the need for an external DC source to excite the rotor winding via brushes and slip rings, or a brushless excitation system featuring higher complexity and cost is the main obstacle for adopting EESG option, especially in off-grid applications.

3.2.2. PMSG

Unlike the WRSG, PMSG is a brushless self-excited synchronous machine. The rotor magnetic flux is produced by permanent magnets. The absence of rotor copper losses reduces the thermal stress on the rotor and guarantees a high power density. Since 1996, PMSG has become more attractive than WRSG due to a decrease in the costs of permanent magnet and power converter [68]. Currently, however, there is a lot of doubt about permanent magnet availability and cost in the near future [69]. This is mainly due to limited global suppliers and probable impact of politics on the stability of permanent magnet market.

Based on the way permanent magnets are mounted on the rotor, PMSGs fall under one of the following categories: (i) surface-mounted PMSG and (ii) inset-magnet PMSG. In the first type, the magnets are placed on the rotor surface, compromising the mechanical integrity of structure with the risk of magnet detachment at high speeds. For this reason, as well as other reasons related to machine's efficiency and power density, surface-mounted PMSGs are preferred for low-speed wind turbines [70]. In the second type, the magnets are inserted into the rotor body, making this design appropriate for high-speed turbines [71]. The inset-magnet PMSG can offer a high-efficiency drive by utilizing the reluctance torque in addition to the magnet torque [72].

In recent years, PMSG has been acknowledged as a dominant solution in direct-drive, small-scale wind turbine systems, in both grid-connected [73–76] and stand-alone applications [24,25]. For large-scale wind turbines, the inset PMSG structure with a salient-pole rotor design provides the highest efficiency among different rotor structures [77]. However, PMSG may not be preferred in large-scale wind turbines as it involves use of large and heavy magnets. To overcome this problem, [78] has proposed a light-weight structure for PMSG, as a solution for large-scale direct-drive wind turbines.

Different configurations of PMSG-based WECS, as well as different control strategies, have been proposed and implemented to demonstrate the efficient performance of PMSG in stand-alone applications [26–28,43,79–83] and hybrid micro-grids [84–86]. Stand-alone configurations of PMSG-based WECS will be discussed in detail in Section 4.

Based on the above discussions, SCIG and PMSG seem to be the most suitable generator types for stand-alone WECS. Therefore, the advantages and drawbacks of these schemes will be compared in the next section.

4. SCIG-WECS versus PMSG-WECS

The comparison in this section will be on the basis of topology, efficiency, reliability, control complexity, cogging torque, noise, and cost.

4.1. Topology

Figs. 6 and 7 show typical topologies for SCIG- and PMSG-based stand-alone WECS, respectively. The obvious difference is the absence of gearbox in PMSG-based configurations, as explained in the previous section. Since PMSG is self-excited, a diode rectifier can be used as the generator-side converter, as shown in Fig. 7(a). In contrast, a VAR compensator, such as a capacitor bank, is required to excite the SCIG if three-phase diode rectifier is to be

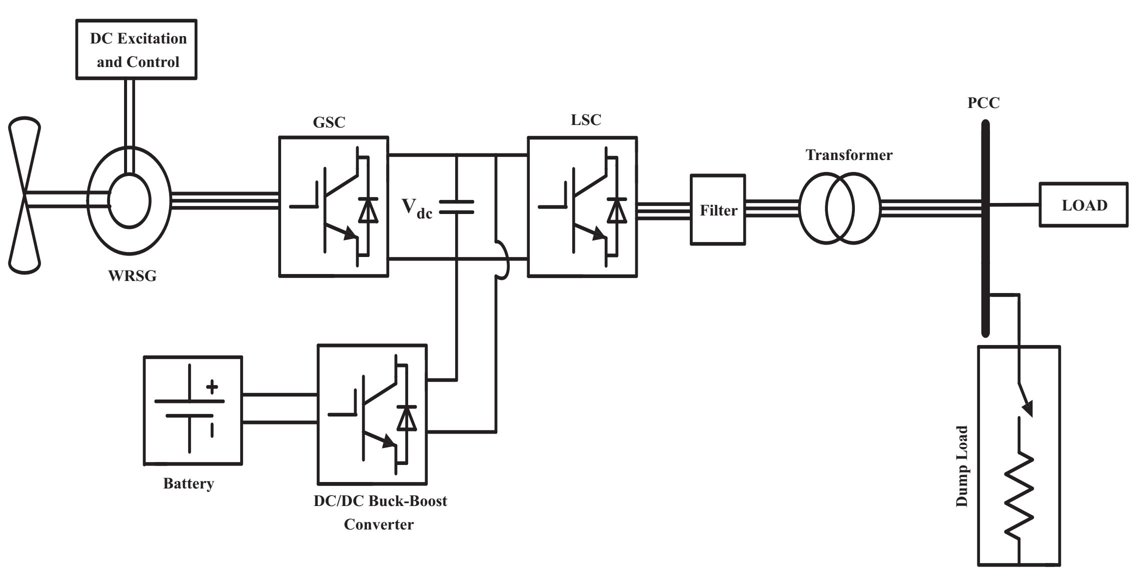

Fig. 5. EESG-based direct-drive stand-alone WECS.

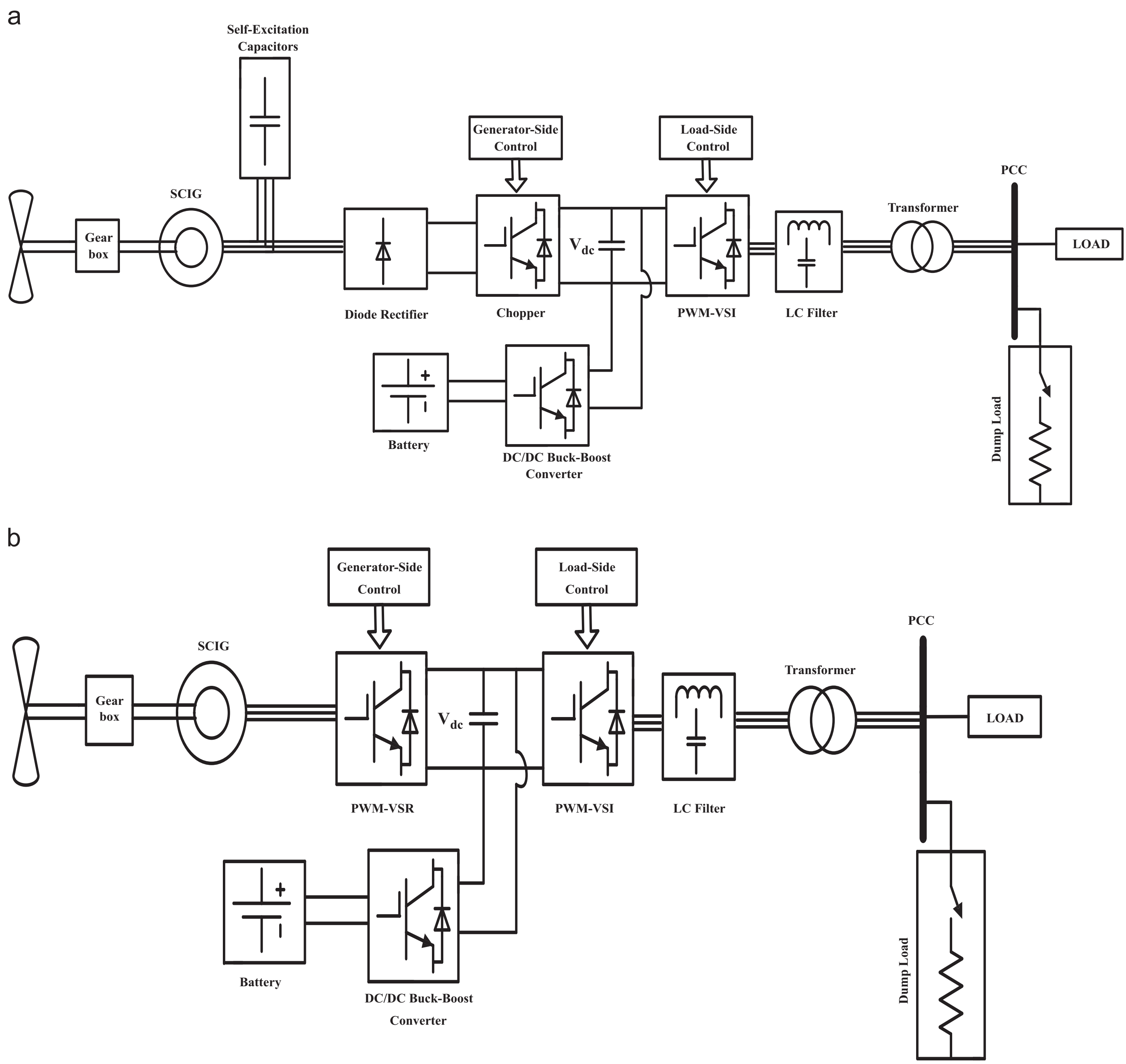

Fig. 6. SCIG-based stand-alone WECS: (a) with generator-side diode rectifier, and (b) with generator-side voltage-sourced converter.

used, as in Fig. 6(a). In both cases, a chopper (e.g., a DC/DC boost converter) is required to control the speed of the generator shaft in order to achieve MPPT. Alternatively, full generator control can be obtained by using three-phase IGBT converters, as shown in Figs. 6(b) and 7(b). This eliminates the need for self-excitation capacitors for SCIG, as the required reactive power is supplied by the power electronic converter itself.

In all topologies shown in Figs. 6 and 7, two-level pulse width modulated voltage-sourced inverters (PWM-VSI) are used as the load-side converters. These converters allow bi-directional power transfer between the DC-link and the PCC. The DC-link provides an energy buffer between the generator-side and load- side converters, allowing for separate control of the converters on the two sides. The battery pack is connected to the DC-link through a bi-directional buck-boost converter, allowing for a low-cost, low-voltage battery unit. The DC-link voltage (V_{dc}) is regulated through power management among the generator, battery and dump load. Due to continuous variations of load and wind speed, power management is a must in stand-alone WECS.

The fact that in the system of Fig. 7(a), a diode rectifier can be used without the need for self-excitation capacitors, is considered a big advantage for PMSG-WECS over SCIG-WECS. The efficient performance of this system has been demonstrated in [26–28,83]. Indeed, it is a trend to use a diode rectifier and a boost DC/DC converter with PMSG-WECS, as a simple and cost-effective option [12,13]. Employing semi-controlled rectifiers is also a possibility [87]. One problem with using diode rectifier as the generator-side converter is the resulting distortion in the stator current waveforms, leading to higher losses and torque ripples in the generator. These drawbacks are avoided in the systems illustrated in Figs. 6(b) and 7(b), where rectification is done by PWM-voltage-sourced rectifiers (PWM-VSR). In fact, the power converter topology employed in Figs. 6(b) and 7(b) is the most commonly-used topology in wind turbine systems [11,13]. This topology,

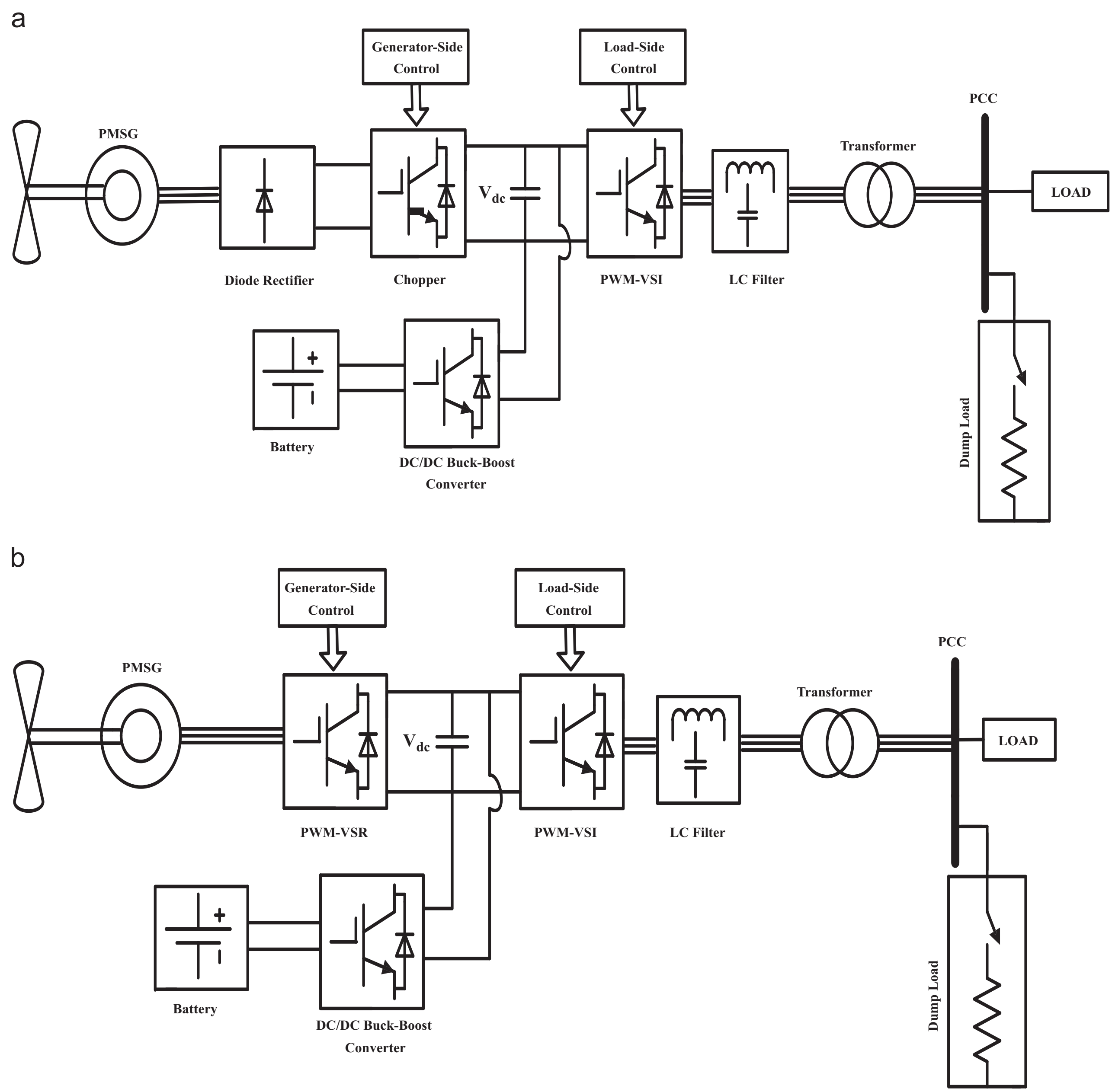

Fig. 7. PMSG-based direct-drive stand-alone WECS: (a) with generator- side diode rectifier, and (b) with generator-side voltage-sourced converter.

highlighted in Fig. 8, is known as two-level back-to-back (2L-BTB) PWM converters. The 2L-BTB is a well-established technology, especially in low-voltage, small-power wind turbine systems, and thus a mature solution for stand-alone WECS.

As the power and voltage levels increase, multi-level (ML) converters are preferred. Compared to the 2L-BTB, ML converters, especially three-level converters, produce much lower switching losses, as well as lower switch stress, harmonic distortion and dv/dt stress on the generator and transformer [88,89]. However, due to higher number of switches, higher cost and control complexity are associated with ML converters. The details of classical and advanced ML converters are beyond the scope of this paper, but have been covered in the literature [90–92]. Fig. 9 shows a three-level neutral point clamped (3L-NPC) converter, which is commonly used in high-power WECS [93].

Although voltage-sourced converters (VSC) dominate the present WECS market due to their mature technology and fast dynamic response, current-sourced converters (CSC) can also be a good alternative, especially in high-voltage applications and when the priority is given to converter cost reduction [94]. Compared to 3L-VSC, CSC has simpler structure with lower switch count and reliable inherent short-circuit protection [95]. The unfiltered AC-side current of a CSC is inherently a 3-level waveform, thus reducing the filtering requirements. CSC can also be constructed as BTB and ML converters. A BTB–CSC is shown in Fig. 10.

The presence of bulky DC-link capacitor and inductor in VSC and CSC topologies reduces their efficiency and shortens their overall lifetime. On the contrary, matrix converter (MC), which is a direct AC–AC converter, has a higher efficiency, longer life and reduced size due to the absence of DC-link energy storage devices [96]. The configuration of a matrix converter, using nine bi-directional switches, is shown in Fig. 11. One of the challenges in MCs that has triggered a good deal of research activity is the necessity of safe commutation due to lack of freewheeling paths [97,98].

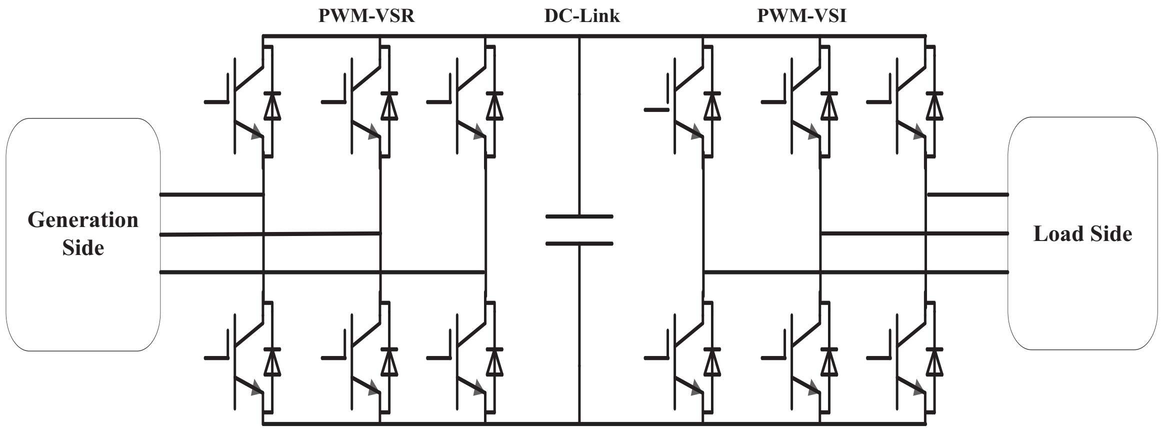

Fig. 8. Two-level, back-to-back voltage-sourced converter topology.

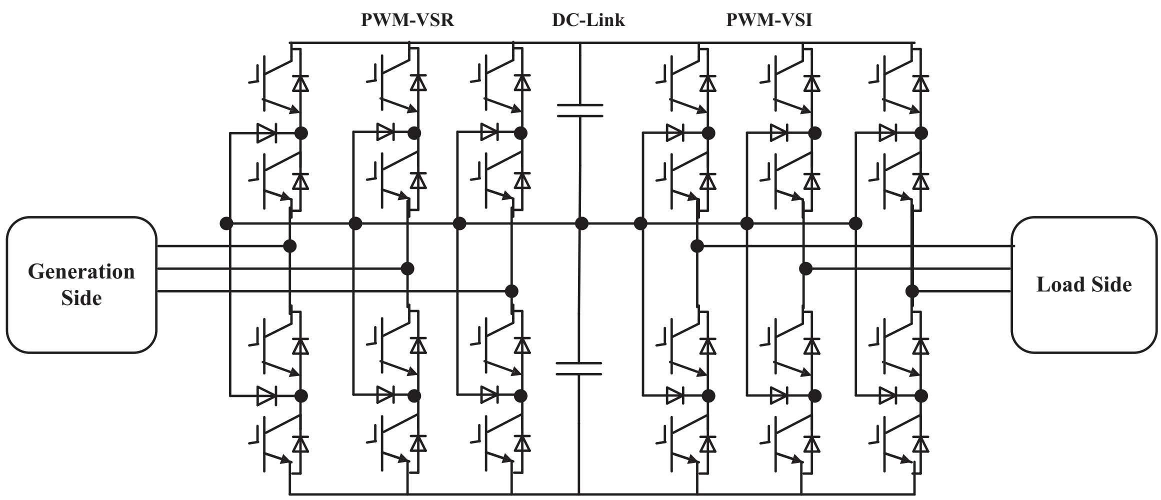

Fig. 9. Three-level, neutral point clamped converter topology.

Among the technologies discussed above, BTB is widely used in wind energy applications. However, a thorough comparative study is required to decide on the optimum power converter topology for a specific wind turbine system. Examples of such studies can be found in [9,13,91,93].

Because of operating at high switching frequencies, PWM converters produce high-frequency harmonics, leading to power quality problems. Thus, these converters require harmonic filters on the generation and/or load sides. Series passive L filter, even though commonly-used, can cause large voltage drops at the fundamental frequency. Hence, LC and LCL filters have become popular. LCL filters offer advantages over L and LC filters in terms of cost and dynamics, due to requiring smaller inductors to achieve the desired performance [99]. Active filters are also a possible solution [100], if economically justifiable.

In isolated WECS, a transformer may be required depending on the level of generated voltage. Star-Delta, Zig- Zag and T-connected transformers are the common types used in WECS [60].

Lead acid batteries (LABs), as a mature and established energy storage technology, still represent a low-cost option for stand-alone WECS [101]. However, they suffer low energy density and limited cycle life. Flywheel, ultra-capacitor and electrolytic hydrogen are other possible options [102].

4.2. Efficiency

Due to presence of permanent magnets in PMSG, it is not necessary to supply magnetizing current to the stator for constant air-gap flux. Therefore, the stator current is only responsible for producing the torque component and hence the PMSG, when compared to SCIG, will operate at a higher PF, leading to higher efficiency. SCIG, in contrast, needs to be connected to an external VAR source, such as self-excitation capacitors, in order to establish the magnetic field across the air gap. This results in a low power factor and efficiency. In general, induction generators are considerably less efficient than synchronous generators with comparable ratings [103]. Nevertheless, simplicity, size and cost factors might prevail over energy efficiency in small-scale WECS.

4.3. Reliability

Reliability of a wind turbine can be measured by frequency and duration of failures in the system [104]. The gearbox, which is required to match the low turbine speed to the high speed required for the generator, requires regular maintenance and is not immune to failure. If it fails, the repair required is a major task. Studies have shown that the gearbox has a very long downtime per failure when compared with other components of WECS [105]. Thus, the elimination of gearbox in direct-drive PMSG-based WECS can significantly improve the reliability of the system. However, direct-drive systems feature higher number of failures in generator and power electronic converters [106] due to direct transmission of wind turbine rotor fluctuations to the generation side. Overall, the reliability of generator and power electronics is affected by the use of direct-drive system although the downtime of indirect-drive systems due to gearbox is definitely much longer

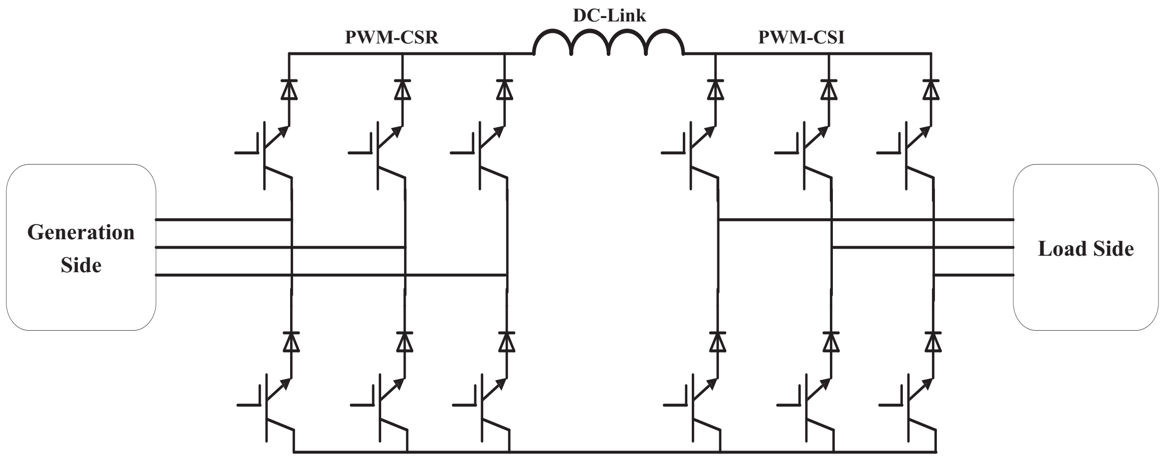

Fig. 10. Back-to-back current-sourced converter topology.

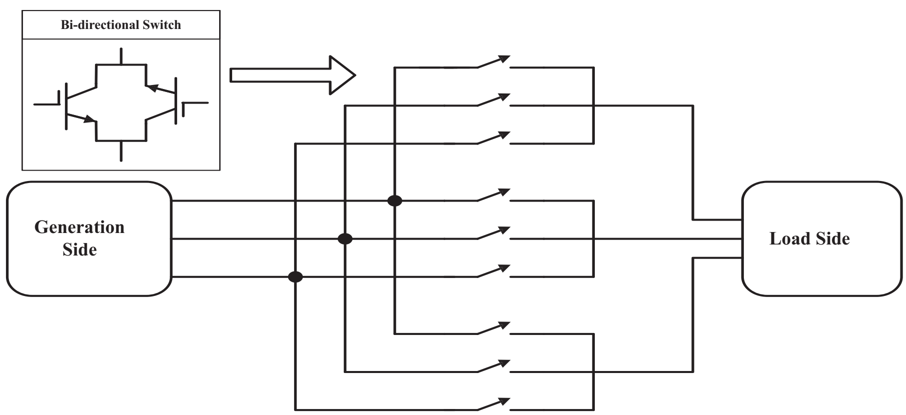

Fig. 11. Matrix converter topology.

than those of power electronics or generator. Moreover, direct drive systems feature larger size and weight, which are considered disadvantages for small-scale wind turbines. Large-scale, modern direct-drive wind turbine systems have been optimized in design by some manufacturers to become comparable in weight to geared systems [68].

Although gearless design is an advantage for PMSG-based WECS over SCIG-based WECS, the fact that the reliability of PMSG can be affected by permanent magnet′s demagnetization and change of characteristics under harsh environmental conditions and at high temperatures, is considered a serious disadvantage.

As far as the generator type is concerned, real data has shown that synchronous generator-based turbines suffer higher failure rates than those using induction generators [107].

4.4. Control complexity

In variable-speed WECS, the operating point can be either below or above rated speed. When operating above rated speed, protection of the turbine comes first. Below rated speed, the speed of the generator shaft is adjusted by the MPPT controller. MPPT is of key importance in wind energy systems and has attracted enormous amount of research activity, aiming to achieve better and faster MPPT techniques. Some of the latest literature on MPPT algorithms can be found in [108,109]. Although many MPPT techniques have shown an excellent performance, some recent measurement data has shown that there is still room for improvements in the MPPT techniques, especially for small-scale wind turbines [110].

SCIG is one of the simplest machines in terms of control requirements. Control algorithms such as direct field oriented, indirect field oriented and direct torque control, are very well-known and well-established. In contrast, one of the drawbacks of PMSG is its control complexity, which is caused by the fact that the magnet excitation cannot be varied and hence the output voltage of PMSG will vary with load. This problem can be solved by capacitor compensation or electronic voltage controller, adding to the control complexity. Zero d-axis current, maximum torque per ampere and unity power factor, are three common methods of PMSG control [12].

4.5. Cogging torque and noise

In PMSG, the interaction between the magnets of the rotor and the slots of the stator generates an undesirable torque, called cogging torque, which causes fluctuations in torque and speed of the machine shaft. Cogging torque results in vibration and noise in the machine, especially at low speed and hence it can negatively affect the cut-in speed of the PMSG turbine [111]. A number of papers have proposed specific designs to reduce the effects of cogging torque in PM synchronous machines [111–113]. Unlike PM synchronous machines, the phenomenon of cogging torque is not significant in induction machines [114]. However, a geared-SCIG turbine has another source of noise as a result of presence of gearbox in the drive train [115]. In summary, both gearless-PMSG and geared-SCIG WECS have a source of noise, which is not so important if the turbine is installed far away from the community. However, the cogging torque of PMSG does always matter,

as it affects the cut-in speed and hence the total kWh production of the wind turbine, leading to a lower capacity factor.

4.6. Cost

In addition to the advantages mentioned earlier for SCIG- and PMSG-based WECS, the decrease in the cost of power electronics and permanent magnet materials in the past few years has made all topologies of Fig. 6 and Fig. 7 more attractive [48].

Compared to the geared SCIG system shown in Fig. 6, the gearless PMSG system shown in Fig. 7 saves on the cost of gearbox. However, the size and weight of gearless PMSG is higher than those of geared SCIG. Furthermore, the multi-pole structure adds to the cost of gearless-drive PMSG system. Moreover, PM generators are generally more expensive than induction generators due to the high price of magnets. However, it has been noticed that the price of PM machines can greatly vary from one country to another based on the availability of permanent magnet materials. For example, cost of a PM machine made in China, where magnets are abundant, is generally lower than cost of a PM machine of the same rating made in Japan, where magnets are rare and on high demand.

The combination of a diode rectifier and a DC/DC converter is less expensive than a switch-mode voltage-sourced rectifier. Therefore, the first configuration is commonly used in small-scale, stand-alone PMSG systems [23]. However, voltage-sourced rectifier is preferred for SCIG due to avoiding a capacitor bank.

For cost comparison purposes, a 30 kW wind turbine is selected as an example for small wind turbines in off-grid applications. Such a turbine can supply power to a small village, a large farm and a small enterprise with an energy storage system. Table 1 shows the prices for a gearless-drive PMSG-WECS and a geared-drive SCIG-WECS with similar power ratings (i.e., 30 kW) [116–118]. The comparison shows the cost advantage of geared SCIG turbine with respect to gearless PMSG turbine. The combined cost of SCIG and gearbox is around 50% of PMSG cost. Although the price difference depends on power rating and varies from one manufacture to another, and from one country to another, the price ratio between geared SCIG and gearless PMSG systems are currently significant due to the involvement of PM materials in the latter system.

Operation and maintenance (O&M) cost is another contributor to a WECS overall cost. O&M cost includes cost for regular inspection, repair, spare parts and insurance [119]. In comparison of a geared-SCIG and a gearless-PMSG system, the O&M is mainly associated with gearbox and generator. The O&M cost for geared-SCIG is expected to be relatively high due to the presence of gearbox, which requires regular maintenance and expensive spare parts if a repair is needed [105]. On the other hand, the gearless-PMSG's O&M cost is due to high rate of failures in generator and power electronic converters [106], but it is still much lower than the gearbox maintenance cost. Insurance of a wind turbine is also counted as a part of O&M expenses. The insurance of a geared-SCIG turbine is considerably affected by the gearbox. The cost of replacing a gearbox can reach 10% of the original construction cost of the wind turbine [120], which defeats the advantage of low capital cost in a geared-SCIG wind turbine. On the other hand, the insurance is generally proportional to capital cost and hence a gearless-PMSG turbine's insurance is negatively affected by its high capital cost, which is expected to increase further in future due to unreliable supply of permanent magnet material. In summary, although the presence of gearbox in a geared-SCIG turbine adds to the O&M expenses, its overall cost, including capital cost, is still lower than a gearless-PMSG wind turbine.

Based on the comparisons from the viewpoints of efficiency, reliability, particularly the length of gearbox downtime, and excitation requirements, the direct-drive PMSG system with diode rectifier, shown in Fig. 7(a), currently represents the preferred topology for small-scale, stand alone WECS. If cost is to be reduced further, without losing the advantages of PMSG, an interesting alternative can be a mixed solution composed of a single-stage gearbox and a medium-speed PMSG. Furthermore, a more efficient and reduced-size PMSG was designed by [121] based on the theory of contra-rotating machine. The contra-rotating machines have two rotors. One carries the magnets and the other carries the armature windings. The idea is to rotate the PM array and the windings in opposite directions. The contra-rotating PM generators have been recommended by [121] for small-scale, stand-alone WECS due to their higher efficiency and smaller volume compared to the conventional PMSG-WECS of the same power rating. Even though the power converters associated with such generator are still not well-established [23], it is a potential for future consideration.

On the other hand, based on the comparison from the viewpoints of reliability, particularly the rate of generator's and power converters' failures, machine's size and weight, control simplicity, cogging torque effect and overall cost, the indirect-drive SCIG system with diode rectifier, shown in Fig. 6(a), wins against the direct-drive PMSG system. If the excitation capacitor bank is to be avoided, a geared-SCIG WECS with a 2-level BTB converter, shown in Fig. 6(b), offers more advantages in term of control and machine's excitation, but with higher cost compared to the system in Fig. 6(a). However, the advantage of low cost in SCIG-WECS over PMSG-WECS still holds. Another important advantage of the system shown in Fig. 6(b), is that the efficiency of SCIG can be improved by controlling the generator-side converter to minimize the generator ohmic losses in addition to its original function in extracting the maximum power [122].

Table 1
Cost Comparison of 30 kW Wind Turbines.

Component	PMSG-WECS [116] US$	SCIG-WECS [117] US$
Blades (3 – Horizontal)	3890	2120
Gearbox	None	4838
Generator	13400	1400
Controller (Including rectifier, dump load and inverter)	8500	8630
Lead acid batteries (144 kW h) [118]	8400	8400

Table 2
SCIG-WECS versus PMSG-WECS.

Topology	Indirect-drive SCIG	Direct-drive PMSG
Common properties	– Brushless machine – No windings in rotor – Full active and reactive power control – Good control bandwidth	
Advantages	– Robust operation – Low cost – Low maintenance – Easier in control	– Gearless – Self excited – High PF operation – High efficiency – No rotor copper loss
Disadvantages	– Gear box losses and maintenance – Need for external excitation – Low efficiency	– Magnet cost – PM Demagnetization – Large size – Complex control – Cogging torque

Moreover, the reliability of geared-SCIG system can be improved by conducting a condition-based predictive maintenance to the system. However, this type of maintenance is based on signals from mechanical sensors which are costly [29].

The main advantages and drawbacks of the geared SCIG and gearless PMSG systems are summarized in Table 2.

In summary, direct-drive PMSGs have been receiving a great deal of attention in wind energy conversion systems due to their distinct advantages of high power density and reliability. However, if construction complexity, control requirements, cogging torque effect, and overall cost are considered, SCIG will prevail. Moreover, PMSG might face a real problem in future due to shortage and monopoly of permanent magnet supply. The source of magnets, especially the Neodymium type, is almost entirely limited to China. This fact is raising concerns about shortage of PM supply in the near future with considerable increase in demand expected due to proliferation of Hybrid Electric Vehicles (HEVs) and Electric Vehicles (EVs) [69].

5. Evaluation of permanent magnet induction generator for stand-alone WECS

As mentioned in Section 4, in spite of its advantageous features, SCIG suffers from low power factor and efficiency as the machine requires magnetizing current from a source of reactive power. If part of the magnetic flux is supplied within the machine, the magnetizing current will be reduced and hence the power factor will be improved. This can be achieved by incorporating permanent magnets within a cage-rotor IG. Such a configuration is called permanent magnet induction generator (PMIG). The stator of the PMIG is similar to that of the conventional IG, but its rotor design is different. PMIG has two rotor parts: a squirrel cage rotor and a PM rotor. Based on PM rotor placement in the machine, there are three possible configurations of PMIG [123]. In the most common configuration, the PM rotor is placed inside the cage rotor with the outer cage rotor linked to the shaft, and the inner PM rotor free to rotate against the shaft [124–126]. As the squirrel cage rotor is

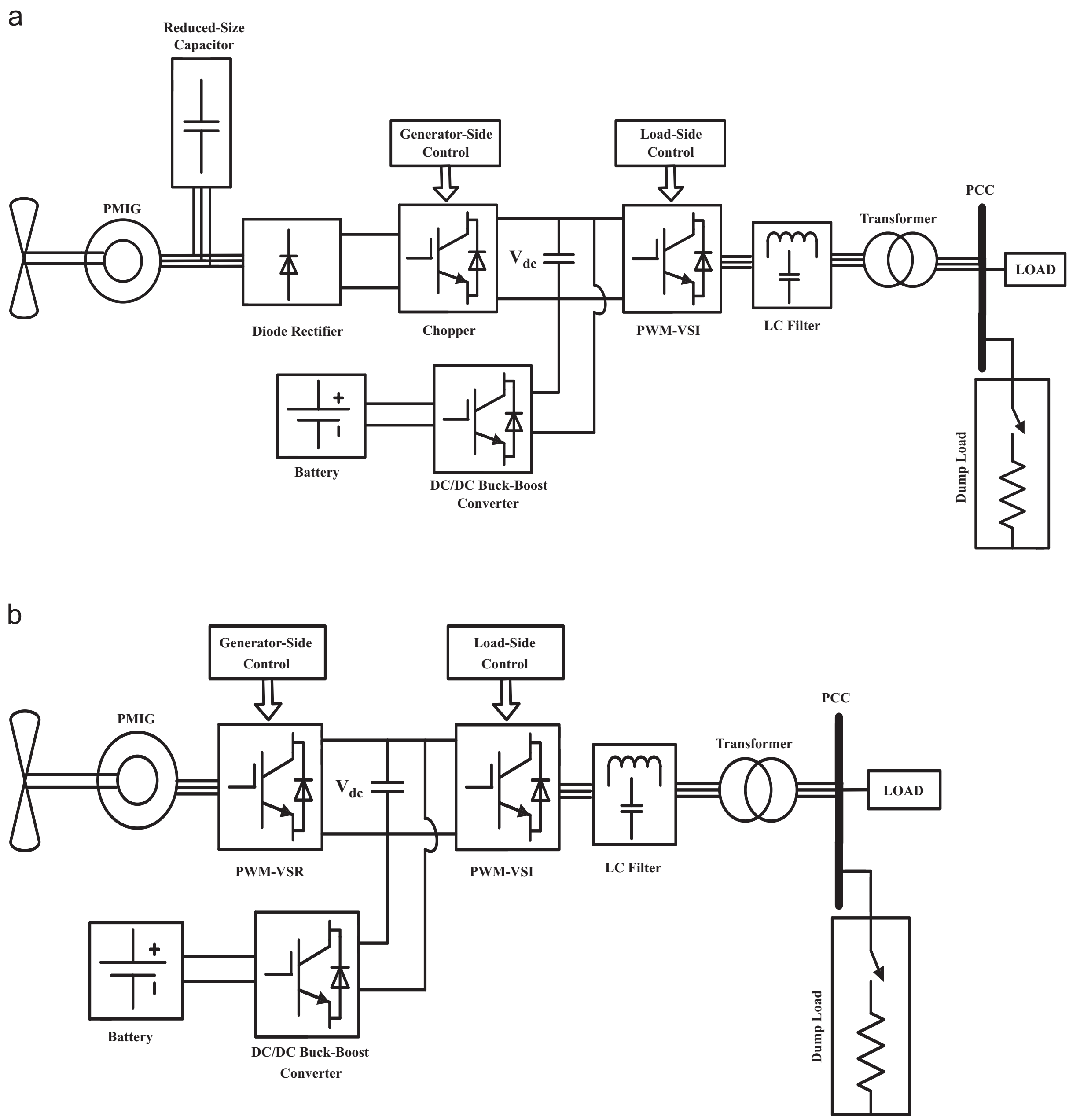

Fig. 12. PMIG-based direct-drive stand-alone WECS: (a) with generator-side diode rectifier, and (b) with generator-side voltage-sourced converter.

uniformly excited from the PM rotor, the need for an external VAR source is diminished. Moreover, PMIG can be directly driven without a gearbox. In other words, PMIG, to some extent, combines the advantages of IG and SG machines. Fig. 12 shows the possible configurations of stand-alone WECS using PMIG. Compared to SCIG-WECS, shown in Fig. 6, the gearbox is no longer an essential component in Fig. 12 and the size of the capacitor bank, shown in Fig. 12(a), is considerably reduced. Theoretically, the magnetizing current, required by the machine, and thus size of the capacitor bank, can be reduced further as the internal voltage induced by the PM gets closer to the stator voltage [123].

Adding an improved power factor and a better performance to the advantages of the SCIG, PMIG has a very good potential to serve as a direct-drive generator in grid-connected [124,127] and isolated WECS [128].

Although it has been considered for direct-drive wind turbines since 1999 [129], PMIG has just been recently recognized in wind energy market. Many manufacturers [130,131] have started considering PMIG as a good alternative for PMSG, especially for small-scale wind turbines. For large-scale WECS, PMIG is still an unattractive option due to high constructional complexity and cogging torque between the two rotors. Reference [126] has proposed minimizing the cogging torque by splitting the PMIG into two PM generators linked by a freely rotating PM rotor; however, such a design adds more weight to the machine. Another drawback of PMIG is the increase in cost due to magnet installation. Table 3 shows the cost information for a 30 kW PMIG-WECS [130]. Compared with PMSG in Table 1, PMIG is slightly less expensive. In order to achieve an accurate evaluation of PMIG, Section 8 will examine the potential of PMIG for a stand-alone WECS with respect to PMSG and SCIG-based WECS.

Table 3
Cost of 30 kW PMIG Wind Turbine.

Component	PMIG-WECS [130] US$
Blades (3 – Horizontal)	3709
Gearbox	None
Generator	12516
Controller (Including rectifier, dump load and inverter)	8225
Lead acid batteries (144 kW h) [118]	8400

6. Potential of switched reluctance generator for stand-alone WECS

According to the discussion in the previous sections, indirect-drive SCIG, direct-drive PMSG and direct-drive PMIG wind turbines are the promising technologies for stand-alone applications. However, SCIG solution is at disadvantage due to issues related to

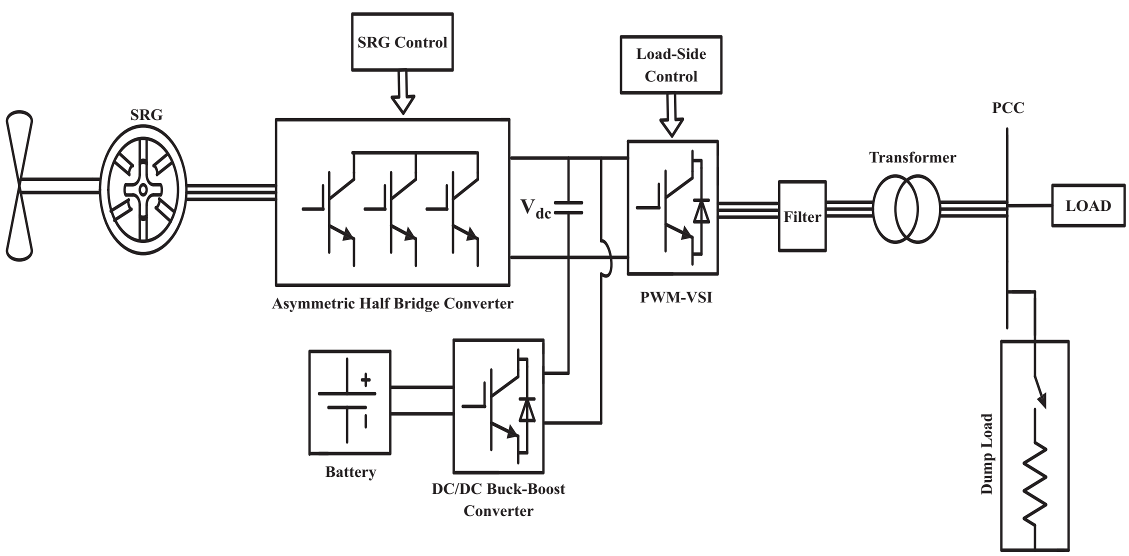

Fig. 13. Stand-alone WECS using direct-drive SRG.

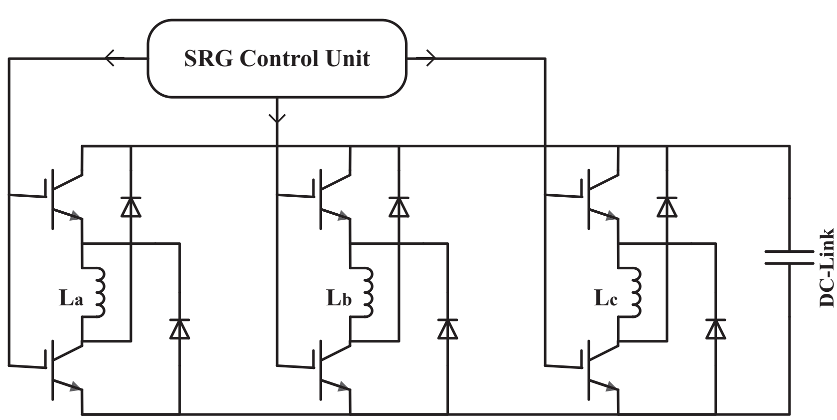

Fig. 14. SRG driven by AHBC.

gearbox and low efficiency, whilst PMSG and PMIG solutions are still suffering from issues regarding magnet cost, PM demagnetization and insecurity of PM future supply. A reliable alternative solution that avoids both gearbox and permanent magnet is offered by direct-drive switched reluctance generator (SRG).

SRG is a structurally simple and robust machine. Its stator and rotor are usually made of steel laminations. The stator consists of a number of salient poles with windings concentrated around them. The rotor consists of a number of salient poles and has neither windings nor permanent magnets, featuring a low moment of inertia [132]. Because of these features, the machine can operate at high speeds and under rough conditions. It can also respond rapidly to any change in the load or speed reference while operating at low speed.

Typical configurations of SRG can be three-phase, 6 stator poles-4 rotor poles (6/4), or 12/8, and four-phase, 8/6 or 16/12. Fig. 13 shows a typical stand-alone WECS using direct-drive SRG.

The operation of SRG is based on sequential excitation of stator windings and movement of rotor based on the tendency to assume the position corresponding to minimum reluctance. As a pair of rotor poles move by a pair of stator poles, the reluctance of the path for magnetic flux and thus the inductance of the stator winding are varied. Minimum reluctance, and thus maximum inductance, is produced when a pair of rotor poles is completely aligned with a pair of stator poles, while maximum reluctance, and thus minimum inductance, is produced in unaligned position. During falling inductance (i.e., from fully-aligned position to fully-unaligned situation), the generator-side converter is controlled to energize the corresponding stator phase. While a stator phase is energized, the desired stator current is realized to achieve the MPPT [133–135]. SRG is normally driven by Asymmetric Half Bridge Converter (AHBC) where each stator phase is fed through two switching devices and two diodes [132,133,136,137]. An AHBC driving a 3-phase SRG is shown in Fig. 14. The cost of AHBC can be reduced by eliminating one switch and one diode in each phase [138]. This is due to the fact that the torque in this type of machine is proportional to the square of the current passing through stator windings, and thus bidirectional excitation is not required. Other options such as C-dump and R-dump converters are also available [139].

In isolated applications of SRG, a DC-link capacitor can be used for excitation. When a phase is excited, the DC-link initially acts as a voltage source and when the phase is generating, the generated energy returns to the DC-link. However, when SRG starts operation, the DC-link is initially discharged and hence an external DC source is required until the required DC voltage builds up. A battery storage system is used for such a purpose.

As a simple, robust, reliable and inexpensive machine with flexible control, SRG has shown a good potential to serve as a direct-drive generator in stand-alone WECS [136,137] as well as grid-connected WECS [140–142]. SRG is competitive in cost with respect to SCIG and is much cheaper than both PMSG and PMIG. Its efficiency is comparable to SCIG or even slightly higher. However, the SRG is a low-efficiency machine compared to the PMSG or PMIG. Moreover, torque pulsation is inherent in the SRG due to the doubly-salient structure of the machine. Thus, torque control is a difficult task for SR machines, especially in generating mode. Another problem faced by SRG is the acoustic noise caused by the torque ripples and the radial vibration of the stator yoke due to the radial magnetic force. These drawbacks may hinder the attractiveness of SRG in stand-alone WECS applications. Therefore, many methods have been proposed to improve the efficiency and minimize the torque ripples of SRG, either by new machine design [143–146] or through new control approaches [147,148].

In summary, SRG has the potential to be a good solution for direct-drive WECS in both on-grid and off-grid applications. Although application of SRG in wind energy systems was proposed in the early 1990s [134], its performance has not been examined beyond simulation and laboratory tests. Thus, when compared with PMSG- and SCIG-WECS, SRG-WECS is still in early stages of development.

7. Main drawbacks of different small stand-alone WECS

Based on the discussions made in the previous sections, Table 4 summarizes the main issues with different generators that might hinder their attractiveness and thus adoption for small-scale, stand-alone WECS applications.

8. Indices for selecting the preferred generator among SCIG, PMSG and PMIG

This section compares the three configurations filtered from all configurations considered, i.e., geared-SCIG, gearless-PMSG and gearless-PMIG. Compared to SCIG and PMSG, PMIG is relatively new to the wind market. The focus of the comparison is on the generator of the wind turbine accompanied by its drive train. Therefore, the three configurations are assumed to

1. have identical rotor blades;
2. have similar VSRs or three-phase bridge diode rectifiers in addition to DC boosters;

Table 4
Drawbacks of different stand-alone WECS configurations.

Topology	Generator	Drawbacks
Indirect-drive WECS	WRIG	– Gearbox problems – Problems of brushes and slip rings – Low efficiency – Limited speed range
	DFIG	– Gearbox problems – Problems of brushes and slip rings – Transient problems due to limited ratings of the rotor power converter
	BDFIG	– Gearbox problems – Complex design and assembly – Large size of the machine – Complex control
	SCIG	– Gearbox problems – Low efficiency
Direct-drive WECS	WRSG	– The need for external DC source for rotor excitation – Brush problems in brushed exciter – Cost and complexity in brushless exciter
	PMSG	– Cost of PM – Demagnetization problems of PM – Insecurity of PM supply in future – Cogging torque effect
	PMIG	– Complex construction – Cost of PM – Demagnetization problems of PM – Insecurity of PM supply in future – Cogging torque effect
	SRG	– High torque ripples – Acoustic noise – In early stages of development for WECS application

3. have similar three-phase VSC-IGBT inverters;
4. have similar types and ratings of storage units;
5. be subjected to the same environmental conditions;
6. have comparable kW ratings;
7. be designed for off-grid application over their entire lifetime; and
8. be land-based wind turbines.

According to the discussions made in the previous sections, Table 5 compares the three recommended systems in terms of different indices. The indices are set up in order, starting by the most important index for a small-scale off-grid WECS supplying a remote community. The top priority in supplying remote areas is given to the reliability of the system, followed by its continuous O&M cost, while the lowest priority is given to construction complexity and noise level, assuming that the turbine is not very close to the community that is supplied. Due to difficulties in giving an exact quantitative analysis (i.e., numbers or percentages), a qualitative comparison is performed based on the discussions conducted in previous sections. For each index, each system is assigned a number (e.g., 1, 2 or 3) to show its rank in that index with respect to the other two systems. If two systems are assigned the same number for a specific index, they are in the same rank and hence they have similar level of advantage for that index. As shown in the table, geared-SCIG system is prominent in 61.5% of the indices whilst gearless-PMSG system dominates in 38.5% of the indices. Gearless-PMIG is similar to the gearless-PMSG in 60% of its advantageous. Therefore, geared-SCIG system prevails in terms of number of indices. However, gearless-PMSG dominates in three of the top priority indices, namely duration of failure, gearbox O&M cost and generation efficiency. Nevertheless, geared-SCIG is dominant in four of the top priority indices, namely frequency of failure, generator O&M cost, kWh production at low speed and capital cost. In order to achieve accurate results, the weight of an index, according to its order, should be considered. Considering the order of each index (i) and rank of each generator (R) provided in Table 5, the credit of each generator (C) is obtained from formula (1).

$$C = \frac{1}{\Sigma_{i=1}^{13}[(i)(R_i)]} \tag{1}$$

It has been found that SCIG scores the highest credit, while the lowest credit is gained by PMIG. Taking SCIG as base, the relative credit of PMSG and PMIG are 87% and 73%, respectively. Therefore, the geared-SCIG proves to be the most suitable for small-scale off-grid WECS, provided that its reliability and efficiency can be improved, while maintaining the advantage of lower overall cost.

9. Conclusion

The paper gave an analytical review of different stand-alone wind energy conversion systems based on possible generator types, available in wind market and reported in the literature. The overview concentrated on the variable-speed turbines. Geared-drive turbines using induction generators and gearless-drive turbines using synchronous generators were considered. The configurations and characteristics of different wind turbine systems were described and discussed along with their advantages and drawbacks. Gearless-drive PMSG-based and geared-drive

Table 5
Comparison of the Geared-drive SCIG, Gearless-drive PMSG and gearless-drive PMIG - WECS configurations.

Order of index	Index name	Details of index	Geared-SCIG	Gearless-PMSG	Gearless-PMIG	Best options	Comments and justifications
1	Reliability	Duration of failure	2	1	1	PMSG and PMIG	No gearbox
2		Frequency of failure	1	2	2	SCIG	Direct-drive WECS suffers higher failure rate as fluctuation of wind rotor is directly transferred to generator and power electronics.
3	O&M cost	Gearbox	2	1	1	PMSG and PMIG	No gearbox in direct-drive turbines.
4		Generator	1	2	2	SCIG SCIG	Generator failures are costly in direct-drive turbines.
5	kWh production	Affected by cut-in, rated and cut-out wind speed	1	2	2	SCIG	Cogging torque in PM generators negatively affect the cut-in speed of the turbine and thus kWh generation.
6	Capital cost	Cost of generator and gearbox (if any)	1	3	2	SCIG	Permanent magnet machines are expensive due to magnets.
7	Efficiency	Accounts for gearbox and Generator loss	3	1	2	PMSG	Gearless PMSG has neither gearbox nor rotor copper losses. It also operates at high PF.
8	Excitation requirements	Reactive power source	3	1	2	PMSG	SCIG is fully externally excited. PMIG is partially externally excited. PMSG is fully internally excited.
9	Magnet problems	Demagnetization and future availability	1	2	2	SCIG	SCIG has no magnets.
10	Control simplicity		1	2	3	SCIG	SCIG is simple in control while fixed magnet excitation in PM machines complicates their controls.
11	Construction simplicity	Number of poles, diameter size, and rotor design	1	2	3	SCIG	Direct-drive PMSG is large and heavy due to multiple-pole construction. PMIG is complicated due to double rotor design.
12	Noise level	Drive train	2	1	1	PMSG and PMIG	PMSG & PMIG have no gearbox noise.
13		Generator	1	2	2	SCIG SCIG	SCIG has no significant cogging torque.

Order of index (1–13) denotes degree of significance/priority (1: highest priority).
The index (1, 2 or 3) denotes superiority (1: the best option).

SCIG-based systems were concluded to be the most desirable solutions among different configurations considered.

The two preferred generator types were compared with each other. The comparison was made based on power electronic converters, gearbox and control requirements associated with the generator type. Construction, efficiency, reliability, excitation requirements, cogging torque and cost including capital as well as operation and maintenance cost of the topology were the criteria for the comparison. In terms of efficiency and reliability, the direct-drive PMSG system is the best option. In particular, the direct-drive PMSG with diode rectifier was found to be currently the most preferred topology for small-scale, stand-alone WECS as it is less expensive compared to direct-drive PMSG with back to back converter. However, in terms of construction, cogging torque, control simplicity and overall cost, geared-SCIG WECS prevails.

The candidacy of PMIG to replace PMSG in a direct-drive wind turbine was discussed. As an induction machine with improved performance, PMIG has a very good potential to be another alternative for PMSG in small-scale WECS. However, constructional complexity and high cogging torque of the machine may make it unattractive for large-scale WECS.

The potential of SRG to serve in wind energy system was investigated. As a simple, robust, reliable and inexpensive machine with flexible control, SRG has been recommended to serve as a direct-drive generator in stand-alone WECS. However, a SRG-based wind energy system is still a comparatively immature technology. Thus, further analytical studies and experimental research will be required before the SRG turbines can be placed in service.

Finally, the three generation systems, namely geared SCIG, gearless PMSG and gearless PMIG systems were compared with one another, as they are suggested by the discussion to be the most top candidates in today's market. A group of indices were used as basis for a qualitative comparison. The system based on geared-SCIG has been shown to be the most appropriate scheme for a small-scale stand-alone WECS, supplying a remote area.

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